Globular Clusters in Fornax: Does M^0 Depend on Environment?

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ABSTRACT

We present the V-band globular cluster luminosity functions (GCLFs) of the Fornax Cluster galaxies NGC 1344, NGC 1380, NGC 1399, and NGC 1404. Our observations reach to $V = 24.8$, roughly one magnitude beyond the GCLF turnover m_V^0, with $\sim 90\%$ completeness. From the amplitude of the galaxy surface brightness fluctuations, we also estimate the number of globular clusters fainter than this cutoff magnitude. The GCLFs of these galaxies are well fitted by Gaussians; the weighted means of their turnover magnitudes and dispersions are $\langle m_V^0 \rangle = 23.88 \pm 0.10$ mag and $\langle \sigma \rangle = 1.35 \pm 0.07$ mag. The assumption of a universal value for the absolute magnitude of the turnover M_V^0 places the Fornax cluster 0.13 ± 0.11 mag more distant than Virgo. However, in light of recent Cepheid and other high-precision distance measurements, as well as ongoing HST observations of GCLFs for the purpose of determining the extra-galactic distance scale, we choose to re-examine the universal GCLF hypothesis. Based on data from groups and clusters of galaxies, we find evidence that M_V^0 becomes fainter as the local density of galaxies increases. We speculate on the possible cause of this trend; if it is confirmed, GCLF observations will be less useful for determining distances, but may provide important information for constraining theories of star formation in primordial galaxy halos.

Subject headings: galaxies: clusters: individual (Fornax) — galaxies: distances and redshifts — galaxies: star clusters — globular clusters: general

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1. Introduction

The globular cluster luminosity function (GCLF) is often employed as a standard-candle distance indicator based on the assumption a universal value for its mean, or turnover, magnitude M^0 (see Jacoby et al. 1992 for a review of the method). Until recently, it was impossible to apply the GCLF method to determine the distances of galaxies further away than Virgo. Now, with HST and improvements in ground-based seeing and instrumentation, it becomes potentially much more powerful for determining the extra-galactic distance scale. Furthermore, new Cepheid and other high-precision local distance measures would allow for a firm calibration of the method.

Baum et al. (1995a,b) have used HST to observe the the globular clusters (GCs) of the Coma galaxies NGC 4881 and IC 4051 down to $V = 27.6$ and $V = 28.4$, respectively. They derive values of the Hubble constant H_0 near 60 km/s/Mpc. Also with HST, Whitmore et al. (1995) studied the GCs of the extremely rich M87 system to two magnitudes beyond M_V^0 (the V-band GCLF turnover) and derived $H_0 = 78 \pm 11$ km/s/Mpc. Only a small part of the discrepancy in derived H_0 values can be accounted for by the different calibrations used by the two groups. This situation leads one to suspect that the GCLFs themselves may be intrinsically different, especially as there remains no firmly established physical basis for assuming a universal M^0. Previously, there have been suspicions that M^0 is different for spirals and ellipticals (Secker & Harris 1993), with the root cause of this difference being metallicity variations (Ashman, Conti, & Zepf 1995), but M_V^0 was assumed not to vary among large ellipticals. As Whitmore et al. candidly remark, this "crucial assumption" of a universal GCLF is "a hypothesis that needs further verification."

In this Letter, we examine the current state of the universal GCLF hypothesis. First, we present new observations of GCs around four Fornax galaxies. Fornax is an important cluster for testing distance determination methods, as it is spatially much more concentrated than Virgo while being at nearly the same distance (e.g. Tonry 1991; Ciardullo, Jacoby, & Tonry 1993). We find that the GCLF exhibits remarkably little variation for these Fornax galaxies. Next, we use independent distance measurements to galaxies and galaxy groups to compare derived M_V^0 values in different environments. We find somewhat startling evidence that M_V^0 becomes fainter as the local density of galaxies increases. Further verification is once again needed, but if the observed trend proves real, it would have major implications for the GCLF method of distance measurement as well as for theories of GC formation. We conclude with a discussion of these implications, in particular how the local galaxy environment may govern the properties of GC populations.

2. Observations and Reductions

We observed the Fornax Cluster galaxies NGC 1316, NGC 1344, NGC 1380, NGC 1399, and NGC 1404 in 1995 August with the Tek 2048^2 #4 CCD detector at the Cassegrain focus of the 4 m telescope at Cerro Tololo. Four 600 s V-band exposures were taken of each galaxy, except NGC 1316, for which five 600 s exposures were taken. We also obtained 2400 s of integration on a background field $1^\circ\!.5$ west of the cD NGC 1399. The image scale was $0''\!.158$ pix^{-1}; however, the chip was slightly vignetted around the edges, and we shifted the telescope $\sim 6''$ between individual exposures, so the final field size which received the full integration time was about $5'\!.1 \times 5'\!.1$. We processed the images as described by Ajhar, Blakeslee, & Tonry (1994) and Blakeslee & Tonry (1995; hereafter BT95). The seeing in the final NGC 1399 image was $0''\!.94$, while the seeing in the other images ranged from $1''\!.03$ to $1''\!.05$. The photometry was calibrated using Landolt (1992) standard stars; there is no

detectable Galactic extinction in the directions of these galaxies (Burstein & Heiles 1984).

After subtracting smooth models of the galaxy surface brightness profiles, we used a version of the program DoPHOT (Schechter, Mateo, & Saha 1993) for the point source photometry. Completeness corrections were determined by scaling and adding grids (so as to avoid artificial crowding) of 32×32 "cloned" PSF stars and then finding them again with DoPHOT. The scaling was done at 0.4 mag intervals; we interpolated to find the completeness corrections at intermediate magnitudes. The images were then divided up into three radial regions: 20-40″, 40-80″, and 80-160″. We settled on a cutoff magnitude m_c of $V = 24.4$ for the innermost region in each galaxy; at this magnitude, the completeness levels for this region ranged from 77% to to 88%. For the intermediate region, the completeness levels were in the same range at $V = 24.8$, so we used this for the cutoff magnitude. For simplicity, we also used $V = 24.8$ for m_c in the outermost region, although the completeness levels for this region ranged from 90% to 96% at this magnitude. The photometric error is typically ~ 0.12 mag at $V = 24.8$. Any objects classified by DoPHOT as extended were excluded from further analysis. Objects brighter than m_c in each region were then binned in magnitude and our completeness corrections were applied. We subtracted the completeness-corrected luminosity function of the unresolved objects in the background field from the luminosity functions of the objects in the program fields to produce the final GCLFs presented below.

After removing all objects brighter than m_c in each region, we measured the PSF-convolved variance, or fluctuations, remaining in the image. Our variance analysis method is described in detail by Tonry et al. (1990). The variance measurement effectively acts as an "extra bin" in fitting the GCLF. BT95 demonstrate how this measurement can be used for deriving GCLF parameters. The conversion from measured variances to GC densities is done in the same way here, but the GC counts are treated differently in that they are binned for more GCLF shape information. In addition, we leave m_V^0 as a free parameter, instead of varying it only within some presupposed acceptable range, as in BT95. A more detailed account of our point source photometry and positions, completeness experiments, and fluctuation measurements will be provided elsewhere (Blakeslee et al. 1996).

3. Results

We defer the analysis of the spatial structure and total sizes of the GC populations and concentrate on the luminosity functions. We also defer any further discussion of our observations of GCs in the giant disturbed galaxy NGC 1316 (Fornax A). The GCLF of this galaxy was not well fitted by a Gaussian model ($\chi^2 \gtrsim 3$ instead of ~ 1) and would require a more thorough analysis than we can provide here.

3.1. The GCLF in Fornax

Figure 1 presents the V-band GCLFs of the four Fornax galaxies. The plotted curves are Gaussians having σ and m_V^0 values which are the weighted means of the values found in our three analysis regions of each galaxy. The values were derived in the separate regions by χ^2 minimizations using the counts brighter than the individual cutoff magnitudes and our variance measurements. For purposes of displaying the GCLFs, however, we used $m_c = 24.8$ everywhere, applied our completeness corrections, then binned the regions all together.

Table 1 lists our final values for the GCLF parameters; they are nearly identical within the errors. The cD NGC 1399 is the only one with a well-studied GCLF. Geisler & Forte (1990) found $m_V^0 = 23.45$ for this galaxy, but assumed $\sigma = 1.20$ mag (these parameters are correlated when the limiting magnitude is near the turnover). Bridges, Hanes, & Harris (1991) used $\sigma \approx 1.40$,

Table 1

Final Fornax Gaussian GCLF parameters.

Galaxy	Type	V_T	σ	$\pm$	m_V^0	$\pm$	N	$\pm$
N1344	E5	10.35	1.35	0.18	23.80	0.25	140	20
N1380	S0	9.91	1.30	0.17	24.05	0.25	375	35
N1399	E1/cD	9.57	1.38	0.09	23.83	0.15	1120	45
N1404	E1	9.98	1.32	0.14	23.92	0.20	300	30

Note.—Columns list: galaxy name, Hubble type, total apparent V-band magnitude (de Vaucouleurs et al. 1991), Gaussian dispersion of the GCLF, V-band GCLF turnover magnitude, and total number of GCs which went into the Gaussian fits (following corrections for incompleteness and background).

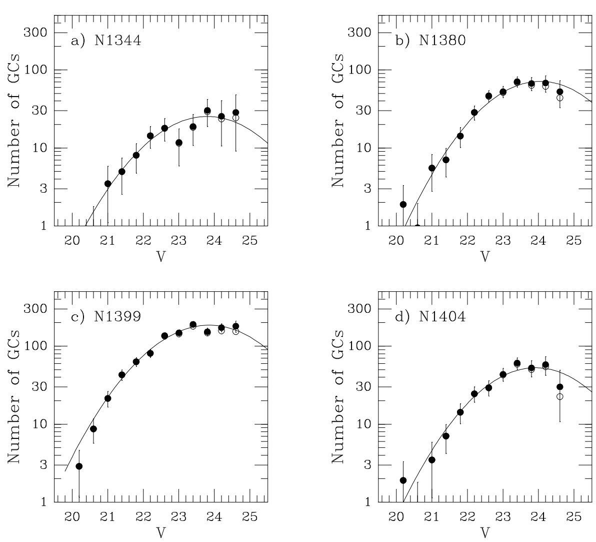

Fig. 1.— The globular cluster luminosity functions of the four Fornax galaxies. Filled symbols represent the final counts following incompleteness and background corrections. Open symbols show what the counts would be with background subtraction, but no incompleteness corrections. Errorbars represent the uncertainties in our corrections and the Poisson errors in the counts.

and found $m_V^0 = 23.85 \pm 0.30$, in close agreement with our value.

As weighted means of the Fornax GCLF parameters, we take $\langle\sigma\rangle_{For} = 1.35 \pm 0.07$ mag; $\langle m_V^0\rangle_{For} = 23.88 \pm 0.10$. Whitmore et al. (1995) found $m_V^0 = 23.72 \pm 0.06$ for M87. We average this with the values for NGC 4472 and NGC 4649 (Secker & Harris 1993) using $(B - V) = 0.75 \pm 0.05$ (Couture et al. 1990, 1991) to find $\langle m_V^0\rangle_{Vir} = 23.75 \pm 0.05$. Thus, assuming a universal M_V^0 yields $\Delta(m - M) = 0.13 \pm 0.11$ for the relative Fornax-Virgo distance modulus. If we were to include NGC 4365 (Secker & Harris 1993) and NGC 4636 (Kissler et al. 1994) in the Virgo average, the relative modulus would drop by ~ 0.1, but both these galaxies are questionable Virgo members (Tully 1987b; Tonry et al. 1990).

3.2. Does M^0 Depend on Environment?

We now forsake the assumption of universality and compare the Fornax GCLF with those observed elsewhere. To do this, we need a self-consistent set of independent distance determinations to galaxies or groups in which m_V^0 has been measured. We start by fixing $(m - M) = 31.0$ as the Virgo distance modulus; this is both the

Jacoby et al. (1992) value and the latest HST Cepheid Key Project result (Freedman et al. 1996). For the relative Fornax-Virgo distance modulus, we take $\Delta(m-M) = 0.25 \pm 0.08$ from an average of the PNLF, SBF, $D_n - \sigma$, SN Ia, and Tully-Fisher methods (Ciardullo et al. 1993; Faber et al. 1989; Riess 1996; Willick 1996).

We use measurements of m_V^0 for M31 (Secker 1992), M81 (Perelmuter & Racine 1995), the Leo group ellipticals (Harris 1990), and the HST limit on m_V^0 for NGC 4881 in Coma (Baum et al. 1995a). The Cepheid distance moduli to M31 and M81 are 24.43 ± 0.10 and 27.80 ± 0.20, respectively (Freedman & Madore 1990; Freedman et al. 1994). This M31 distance modulus is the proper one to use, as it is the one assumed by Jacoby et al. (1992) and is consistent with the more recent HST Cepheid distances. For the Leo group, we average the HST Cepheid distance to the spiral M96 (Tanvir et al. 1995) with the PNLF and SBF distances to the ellipticals (Ciardullo et al. 1993) and get $(m-M) = 30.2 \pm 0.13$. The relative Virgo-Coma distance modulus is well determined at $\Delta(m-M) = 3.71 \pm 0.10$ (e.g. van den Bergh 1992; Whitmore et al. 1995). Finally, in an effort to preserve neutrality in the controversy over the RR Lyrae calibration (see van den Bergh 1995), we omit the Milky Way from our discussion, remarking only that recent MW M_V^0 values have ranged from -7.29 ± 0.13 (Secker 1992) to -7.60 ± 0.11 (Sandage & Tammann 1995; see also the discussion by Baum et al. 1995a).

Figure 2 shows the resulting M_V^0 values plotted against the the velocity dispersions of the groups and clusters, from Tully (1987a) and Zabludoff, Huchra, & Geller (1990). We use velocity dispersion as the most convenient indicator of the depth of the local potential well; it closely correlates with Tully's estimated group densities and with cluster richness. There is a trend of decreasing turnover luminosity with increasing local density. The offset in M_V^0 between the small groups and Fornax/Virgo is 0.4 mag. The use of the straight Cepheid distance to Leo would move its M_V^0 brighter by 0.1 mag, further away from the other ellipticals; the inclusion of NGC 4365 and NGC 4636 would move the Virgo M_V^0 fainter. In addition, the preliminary result $m_V^0 \approx 28.0$ ($M_V^0 \approx -6.7$) for IC 4051 (Baum et al. 1995b) indicates that there may be *another* ~ 0.5 mag offset in M_V^0 for the very rich Coma cluster. Thus, we believe we are seeing real evidence for an environmental dependence of M_V^0.

4. Discussion

We have found that the GCLF is remarkably constant within the Fornax cluster, but, as Figure 2 shows, varies with environment. Ashman et al. (1995) suggested that metallicity differences result in M_V^0 values which are systematically brighter by ~ 0.15 mag for spirals. Large ellipticals usually do have higher metallicity GC populations; however, NGC 4881 in Coma has a GC color/metallicity distribution similar to that of the MW (Baum et al. 1995a), yet its M_V^0 is very faint. In addition, the Leo elliptical NGC 3379, with its relatively high metallicity GC population (Ajhar et al. 1994), has an exceedingly bright M_V^0, though with a large uncertainty (Harris 1990). Finally, we note that the magnitude of the environmental effect we propose is a factor of 3-6 larger than the Ashman et al. M_V^0 metallicity shift.

We suggest that the most straightforward way to produce the present-day near-Gaussian GCLF is to assume that two simultaneous and competing effects were operating when GCs formed: a "creation" process which preferentially created low-mass GCs, cutting the mass function off at the high end, and a "destruction" process which inhibited the formation of, or quickly destroyed, low-mass GCs. If each process operated in a manner which was independent of the details of the environment, then the final mass (luminosity) function would be universal, but if one depended more sensitively on environment than did the other, the final mass function would vary.

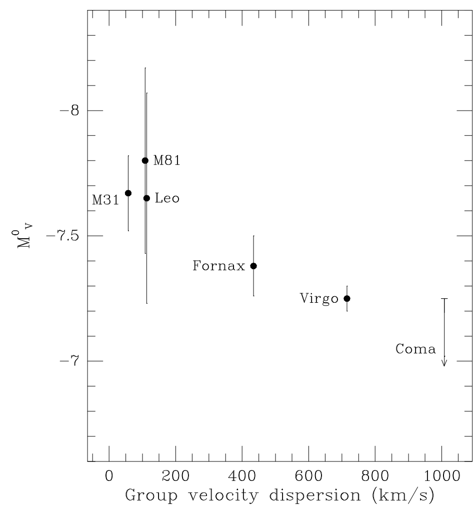

Fig. 2.— The GCLF turnover magnitude M_V^0 plotted against the velocity dispersion of the host galaxy's environment, used as a measure of the local density. See text for details.

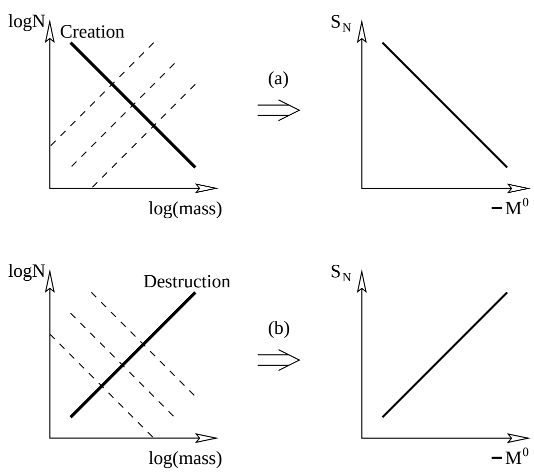

Fig. 3.— The effects of variable GC creation/destruction mechanisms. In part (a) the GC creation process, shown as a power-law growing to smaller mass, is universal (dark solid line), and the destruction process, a power law which wipes out low-mass objects, varies with environment (dashed lines). Since the total number of GCs is the integral under the intersecting creation/destruction lines, this situation results in an anti-correlation between GC specific frequency S_N and GC mean logarithmic luminosity $-M^0$. In part (b) the creation process (dashed lines) varies with environment, while the destruction process (dark solid line) is universal. The result here is a positive correlation between S_N and $-M^0$.

This situation is schematically illustrated in Figure 3, where we use S_N for the GC "specific frequency" (number of GCs per unit luminosity of the host galaxy). In Figure 3a, we assume that the creation process is relatively universal, but that the destruction process varies. This leads to M^0 being variable, and predicts an inverse correlation between the number of GCs formed and their mean brightness. On the other hand, if the destruction process is constant and the creation process is more variable we will again get a variable M^0, but with a direct correlation between the number of GCs and their luminosity, as shown in Figure 3b.

Empirically, we think we see evidence for the latter sort of behavior among "coeval" galaxies, i.e., those located within the same physical association. In Virgo, for instance, M87 has a very large S_N and a slightly brighter M^0 than its close neighbors, and similarly in Fornax for NGC 1399. In this context, the GCLF would depend on the extent to which the host galaxy dominated its local environment. On the other hand, the main point of this paper is that we see the former behavior among very "heterogeneous" systems of galaxies. Young groups dominated by spirals have fewer GCs than galaxy clusters such as Virgo, which in turn may have fewer than rich clusters such as Coma, and we find that the central luminosity of the GCLF is declining along this sequence.

As an example of how such an interplay of opposing processes might work in practice, we consider the common picture of structure formation through gravitational instability. Here, the "creation" process is the primordial spectrum of density fluctuations which favors low-mass clusters, and the "destruction" process is the inhibition of the collapse of low-mass objects resulting from the Jeans mass. In this picture, the Jeans mass can be a very rapidly growing function of time (Tegmark et al. 1996), and the densest systems of galaxies, forming first, would have experienced a less restrictive low-mass cutoff and hence have

more, and fainter, GCs. This is precisely the case depicted in Figure 3a.

Harris & Pudritz (1994) have proposed a detailed astrophysical theory of GC formation which is perhaps more illustrative of the "coeval" case of Figure 3b. They suggest that the "creation" process is made more efficient by the larger external pressures of dense environments. Their "destruction" process is the tidal disruption and evaporation of low-mass GCs, and this might be less sensitive to environment (although see Murali & Weinberg 1996). Of course, if the cutoff is very abrupt (a steep "destruction" line), then M^0 will not correlate very strongly with S_N.

We do not have better "creation" and "destruction" processes to offer than have been advanced elsewhere, but we believe that this description is a profitable way to frame the discussion. Until now, the assumed constancy of M^0 has been a serious obstacle to reasonable models for GC formation, so we conclude by reemphasizing our primary point. The GCLF apparently *does* depend on environment, with M_V^0 being fainter in denser regions, although it may be remarkably constant within a single group of galaxies. This dependence will present challenges for the use of the GCLF as a distance indicator. On the other hand, it opens the door for correlations between M^0 and S_N, and M^0 and environment, which may yield valuable insights into the conditions and processes which prevailed at the time of GC/galaxy formation.

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